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TECHNOLOGY FOR SATELLITE POWER CONVERSION

by

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NASA Technical Officer: W.M. Krawczonek

Prepared for

National Aeronautics and Space Administration
Lewis Research Center
21000 Brookpark Road
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GEORGIA INSTITUTE OF TECHNOLOGY
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1. Introduction

The work in this reporting period has been concentrated on electronically calibrating the bolometer detectors. The calibration is necessary for two reasons: first, the power delivered to the rectifying circuit must be known in order to choose a diode with the appropriate barrier height, and second, the power captured by the antenna must be measured if the efficiency of the rectenna is to be divided into antenna efficiency and rectification efficiency. The millimeter wave region operation of the bolometers has been simulated with a VHF (10-90 MHz) test signal. These detectors are accurate to within roughly 10%. The typical responsivity of the bolometers is 10 volts/watt and the NEP at 20 Hz is 5×10^{-9} $W(Hz)^{-1/2}$. A paper titled "Measurement Techniques for Substrate Mounted MMW Antennas" was presented at the Conference on Millimeter Wave/Microwave Measurements and Standards for Miniaturized Systems, 6-7 November 1986 in Huntsville, Alabama and is included in Appendix A.

2. Summary of Work Completed.

Accurately calibrating the bolometers was deemed necessary if the effect of the substrate, antenna efficiency, and rectification efficiency are to be separated in the overall rectenna process. Further, the voltage developed across the terminals of the antenna should be known in order to choose a diode with the proper characteristics for the rectifying circuit. Recent work by Boyakhchyan, et al.[1] and Ashok[2] has shown how the parameters of Schottky diode rectifiers should be adjusted for different input power levels. The results of numeric calculations in this work show that choosing the proper parameters makes a significant difference in conversion efficiency.

The responsivity (volts/watt) of the bolometer is of primary interest because it gives the ratio of detector voltage output to VHF or millimeter wave (MMW) power absorbed under a given bias current. The responsivity of the bolometer can be determined from a series of dc measurements. Experiments carried out at 10-90 MHz showed that this method of determining the responsivity accurately measures the applied power to within roughly 10%.

For small applied power, the resistance of the bolometer can be modeled by

$$R = R_o + \beta P, \tag{1}$$

where R_o is a cold resistance term and P is the power dissipated in the bolometer. By taking the derivative of the resistance with respect to power, we get β which is the measure of how the resistance changes with applied power. When operating as a power detector, a constant current is supplied to the bolometer so that the change in resistance due to an applied VHF or MMW signal can be measured by observing the change in voltage across the detector. The responsivity is given by

$$\mathcal{R} = \beta I_{bias} \text{ (volts/watt)}, \tag{2}$$

and the detected power is given by

$$P = V_{detector}/\mathcal{R} \; . \tag{3}$$

Since the detector is biased with a constant current, the VHF or MMW signal must be modulated in order to measure the change in bolometer resistance. $V_{detector}$ is equal to the difference between the bias voltage and the voltage across the bolometer when the power is applied. Most often $V_{detector}$ is measured with a lock-in amplifier.

The procedure to determine the responsivity starts by measuring the resistance versus bias power of the bolometer. The voltage across a 1k ohm precision metal film resistor in the current biasing circuit is measured to determine the bias current. The voltage measurement across both the metal film resistor and the bolometer is made with 5-1/2 digit multimeters. The circuit used to make the resistance versus bias power

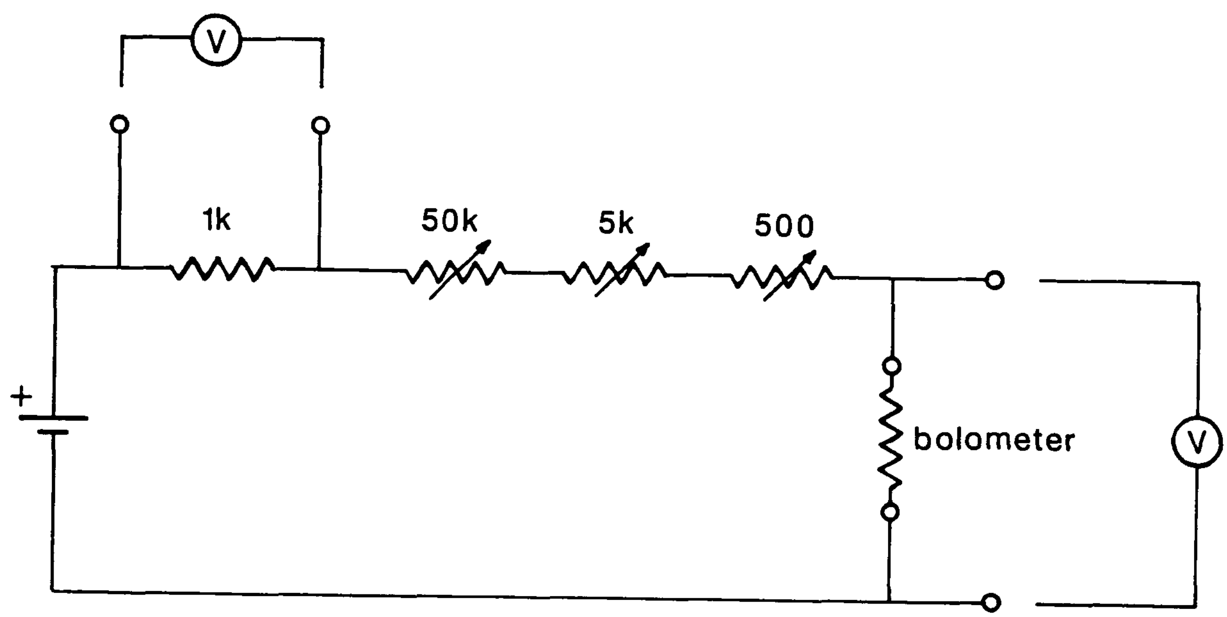

Figure 1. Bias Power Versus Bolometer Resistance Measurement Circuit.

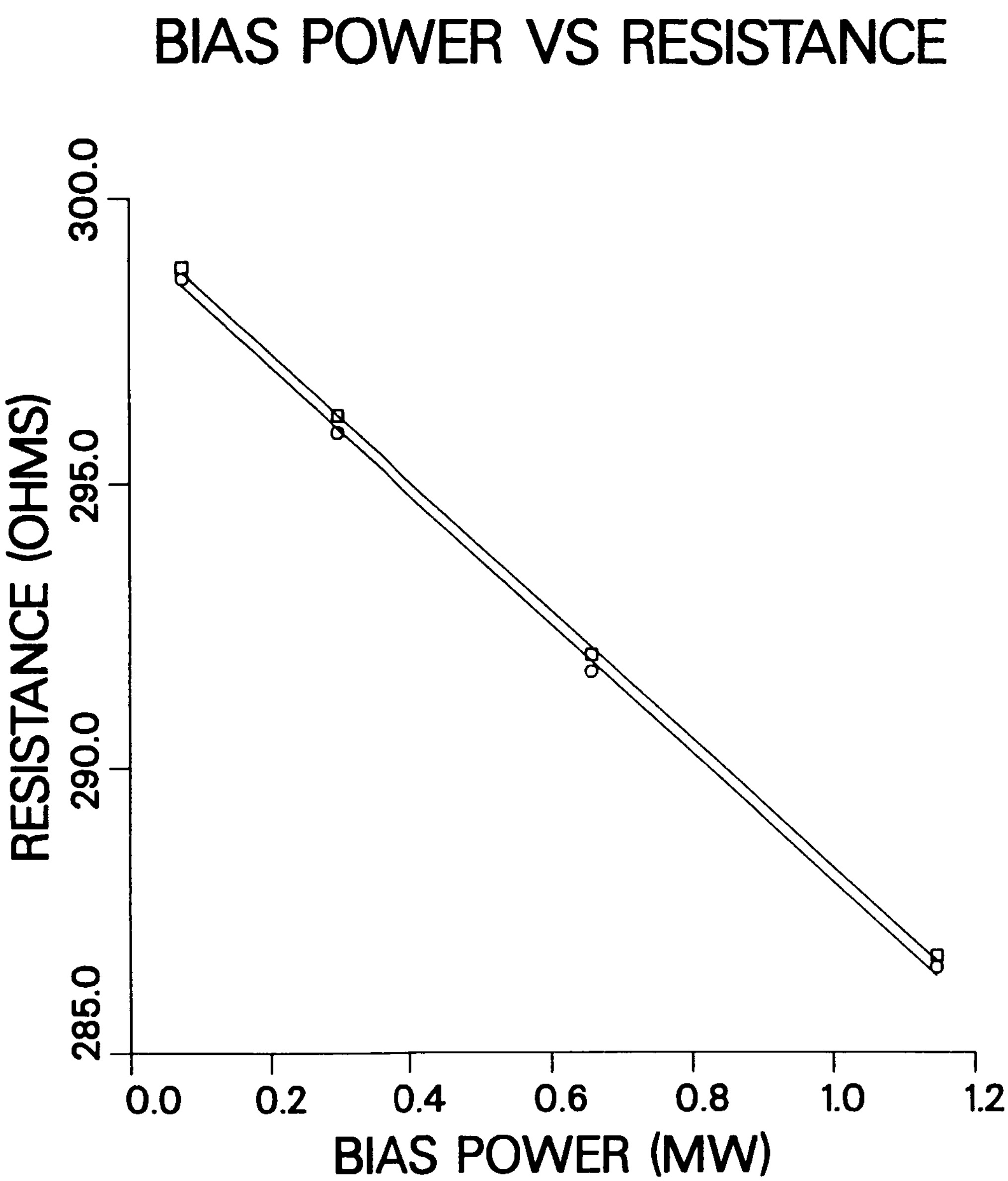

Figure 2. Sample Plot of Bias Power Versus Bolometer Resistance

measurements is shown in Figure 1, and a typical resistance versus bias power plot is shown in Figure 2. In the figure, two lines are plotted which represent measurements taken several hours apart. It is seen that, even though the absolute resistance has changed over time, the slope of the line (and thus the responsivity) has not changed.

The responsivity is calculated by taking the slope of the line at the desired bias power. Since the responsivity is directly proportional to the bias current, a larger bias current is desirable, although the bias power plus the detected power should not be too large to cause the bolometer to be unstable.

The responsivities for 10 different bismuth bolometers are given in Table 1. All of the bolometers were 10 microns wide and 1500 Angstroms thick. The lengths of 80, 40 and 20 microns were chosen because the horseshoe shaped bolometer used in the antennas is a parallel combination of one 40 micron bolometer and two 20 micron bolometers[3]. An additional 10 micron Bi-Au contact region is added to each end of the bolometer so that the bolometer can be contacted to the test circuit via large gold pads.

A VHF test circuit was assembled to test the accuracy of the dc measured responsivity. The idea was to calculate the detector responsivity by the dc measurement technique, and then apply a known VHF signal to the bolometer and compare the detector measured power with the actual power applied. The thermal time constant of the bolometer is too long to track the VHF signal, so the detector will measure the rms power. There is no difference between the operation of the bolometer at VHF and at MMW frequencies since both signals are faster than the time constant of the bolometer. Therefore, this is a meaningful way to test if the responsivity calculated from the dc bias power versus bolometer resistance plot will be accurate at millimeter wave frequencies.

The VHF test circuit is shown in Figure 3. The VHF signal is turned on and off at a given modulation frequency (10-500 Hz) for the operation of the lock-in amplifier. A high pass filter

	BOLOMETER LENGTH (microns)		
	80	40	20
Responsivity (volts/watt)	4.8	7.0	2.8
	11.7	9.0	9.8
	5.4	16.1	6.7
			2.7

Table 1. dc Responsivities for the Different Length Bolometers.

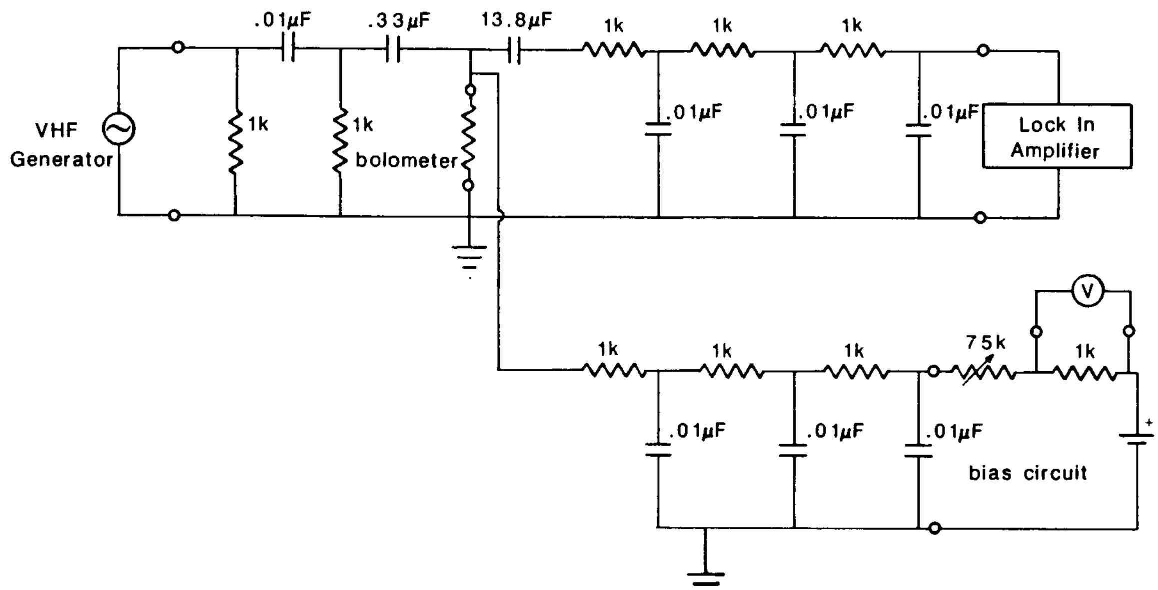

Figure 3. The VHF Test Circuit

is placed after the VHF generator to ensure that no remnant of the modulation signal is introduced into the circuit. The 3-stage low pass filters between the bolometer and the bias circuit and between the bolometer and the lock-in amplifier have over 80 dB attenuation at 10 MHz. The low pass filter to the bias circuit is necessary to isolate the VHF generator and the bias supply. The low pass filter to the lock-in amplifier is needed to prevent demodulation of the VHF signal on the nonlinear elements of the preamp. Such demodulation yields erroneously large detector voltage measurement. Blocking capacitors are used to prevent the dc bias current from entering the VHF generator or the lock-in amplifier.

The first measurement performed on the VHF test circuit was to compare the change in bolometer resistance with dc power and VHF power. This was done by first selecting a bias point for bolometer. Then additional dc power was added to the bolometer, and the change in resistance was noted. The bolometer was set back to the bias point and an equivalent rms VHF power was applied. The change in resistance was measured by a lock-in amplifier. The VHF signal was turned on and off at a 10 Hz rate, and the voltage measured on the lock-in amplifier was equal to the rms value of the bias current multiplied by the change in resistance. The results are shown in Table 2. In eight of the ten bolometers shown, the agreement was 5% or better.

In the second measurement, the VHF power measured by the bolometer was compared to the actual power applied to the detector. First, the dc responsivity of the detector was measured, and the bolometer was biased with an appropriate current (1-2 mA). A modulated VHF signal with known power (approximately 40% of the dc bias power) was applied to the bolometer. The detector voltage, measured with a lock-in amplifier, was divided by the dc responsivity to yield the measured power. The percent difference between the measured power and the actual power was shown in Table 3 for the different length bolometers. In general, the bolometer measured power was about 10% less than the actual power.

	BOLOMETER LENGTH (microns)		
	80	40	20
% difference in resistance	3.5	10.9	3.5
	4.3	2.9	1.67
	16.9	5.1	5.0
			2.6

Table 2. Percent Difference Between the Change in Resistance of the Bolometers for Equivalent dc and VHF Power.

	BOLOMETER LENGTH (microns)		
	80	40	20
% difference in measured and actual VHF Power	9.8	10.8	8.8
	10.7	19.4	2.1
		6.8	15.8
			24.9

Table 3. Percent Difference Between the Measured and Actual VHF Power Applied to the Bolometers.

The dc resistance measurements of the 20 micron bolometers were the largest source of error in the responsivity calculations of these elements. These measurements were often at or just below the specified accuracy of the 5-1/2 digit multimeter used in the experiment. The data for these bolometers is included for completeness. The difficulties in measuring the small changes in resistance will not be a problem for the antenna measurements since the 80 micron bolometer's resistances are four times greater than the 20 micron bolometers.

The VHF signal was increased from 10 MHz to 90 MHz with no change in measured power. 90 MHz was the upper limit because of the bandwidth of the oscilloscope used to measure the actual VHF power.

The effect of the modulation frequency of the VHF or millimeter wave signal has also been explored in the experiment. The thermal time constant of the bolometer is a measure of how quickly the detector responds to changes in temperature. The detector voltage signal for a 20 micron long bolometer and the VHF signal modulated at 100 Hz are recreated in Figure 4. (The frequency of the VHF signal is not depicted accurately for clarity.) The exponential rise and fall in the detector voltage is caused by the exponential increase and decrease in the bolometer resistance and hence the exponential increase and decrease in the bolometer temperature. Clearly, the modulation frequency should not be set so that the detector voltage does not reach it's steady state value. If the detector voltage is large, it can be read on an oscilloscope as the difference between the two steady state values (as in Figure 4). Using a lock-in amplifier to measure the detector voltage places further restriction on the modulation frequency. Typically, the lock-in amplifier measures the rms value of the detector signal. If the detector signal is a square wave, then the detector voltage is twice the reading of the lock-in amplifier. If, however, the exponential rise and fall is appreciable in the detector signal, the lock-in amplifier reading will be less than half of the detector voltage. This last situation must either be taken into

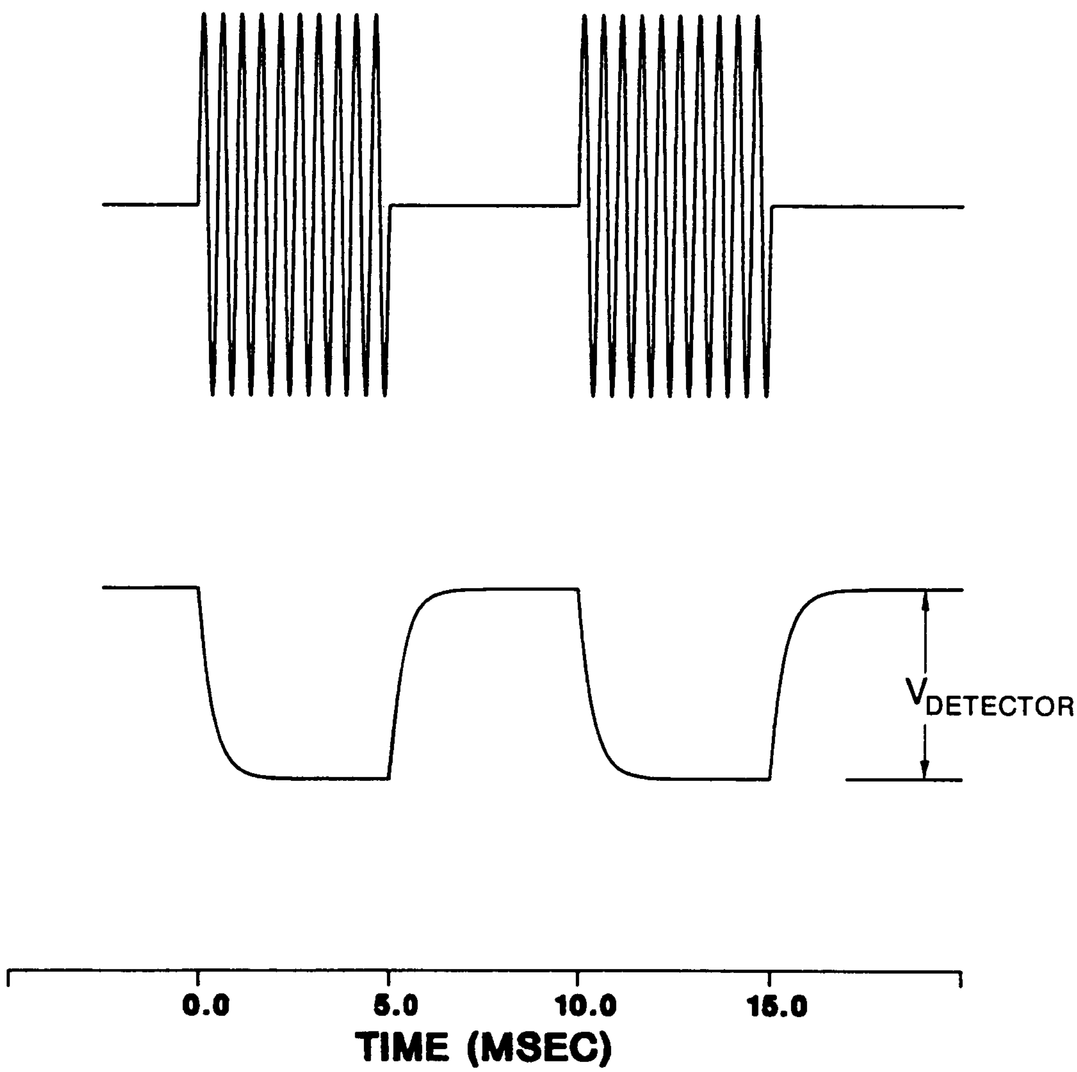

Figure 4. Detector Voltage for a 20 Micron Bolometer with 100 Hz Modulation Frequency.

account when calculating the detector voltage or avoided altogether.

Figure 5 shows the rolloff of the normalized detector voltage measured by a lock-in amplifier for several different length bolometers. From the plot, the longer bolometers exhibit a faster rolloff. The thermal decay time constant for a thermal detector can be calculated from

$$\tau = \frac{1}{2\pi f^*} \tag{4}$$

where f^* is the frequency where the detector voltage rolls off to $2^{-1/2}$ of its dc value. The thermal decay time constants for the various length bolometers have been calculated and are compiled in Table 4. The shorter bolometers have the smaller time constants because they have smaller thermal mass.

The noise equivalent power (NEP) of the bolometers was calculated with the expression

$$NEP = V_{noise/R} \tag{5}$$

the noise voltage, V_{noise}, was measured with a PAR model 124 with model 116 preamp in the direct mode. The bolometer was biased at its operating point and the noise voltage was read with the chopping frequency set at 20 Hz. The 10% noise equivalent bandwidth filter was used in the measurement. The average value of the NEP was 5 x 10^{-9} watts $(Hz)^{-1/2}$.

3. Conclusions and Future Work

The responsivity of the bolometers can be determined by the series of dc measurements. The typical responsivity for the detectors is 10 volts/watt and the typical NEP at 20 Hz is 5 x 10^{-9} watts $(Hz)^{-1/2}$. The responsivity and NEP have been experimentally verified at VHF, and the responsivity is accurate to within about 10%. There should be no degradation in accuracy at MMW frequencies.

It was necessary to calibrate and confirm the accuracy of

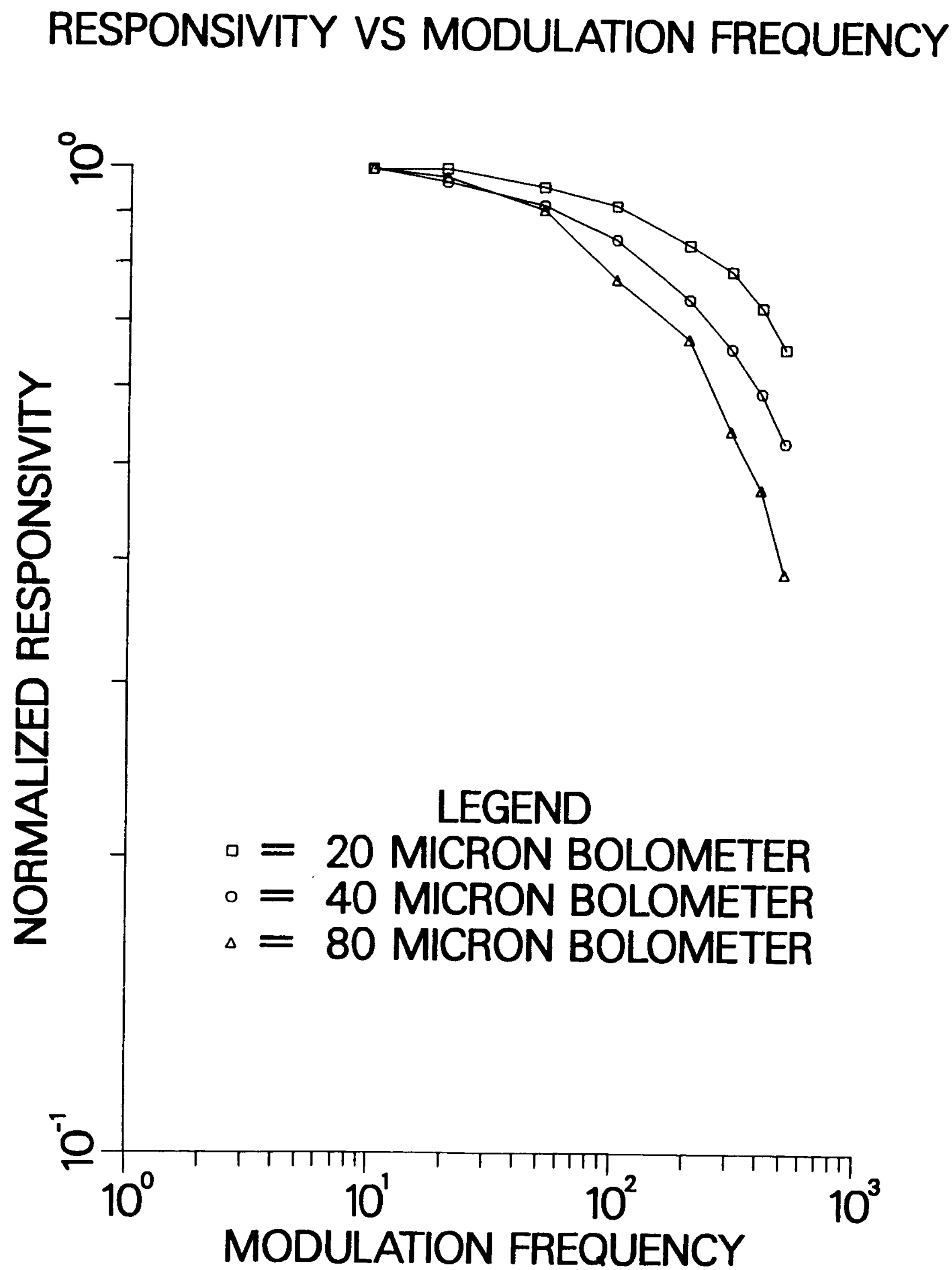

Figure 5. Roll-off of the Normalized Responsivity for the Different Length Bolometers.

Bolometer Length (microns)	Thermal decay Time Constant (msec)
20	0.38
40	0.72
80	1.12

Table 4. Thermal Decay Time Constants of the Different Length Bolometers.

the bolometers for two reasons. First, the power present at the antenna terminals must be known to choose a diode with the best characteristics (e.g., barrier height). Secondly, the relative efficiency of the antenna and the rectifying circuit can be determined.

Presently, preparations for the last set of antenna measurements are underway. There are two objectives of these measurements:

1. To determine, first, the power density of the MMW field (at 230 GHz) presented to the antenna, and then measure the power received by the antenna. From this, the antenna efficiency can be calculated.
2. By measuring the power detected by the bolometer, the optimum diode characteristics for the rectifying circuit can be calculated.

After these measurements, work will begin on rectennas with commercially available diodes bonded into the rectifying circuit. Diodes made for operation at 230 GHz have been denoted by Hughes Aircraft Company in exchange for test results. If these diodes are unsuitable for the power level at the antenna, other diodes can be used at an operating frequency of around 100 GHz.

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